North America Modeling Compendium and Analysis

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Model Comparison Table for: a) Ability to perform CA-US-MX electricity market opportunities and b) Ability for analyzing power system with high penetration of variable generation and other innovative generation, transmission, and control technologies

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Note: models are classified into

1) Production cost model: **PROD**
2) Expansion planning model: **EXP**
3) General equilibrium model: **EQU**

PNNL, March 22, 2016

Comparison table

Features	Why it is important?	PROMOD	PLEXOS	MAPS (GE)	Grid View (ABB)	FESTIV (NREL)	REEDS (NREL)	UPLAN (LCG)	GTMax (Argonne)	SCOPE (Nexant)	NEMS (EIA)	MARKAL (ETSAP)	RIM – current version (PNNL)	GCAM	Haiku	E4ST	Aurora
		PROD	**PROD**	**PROD**	**PROD**	**PROD**	**EXP**	**PROD**	**PROD**	**PROD**	**EXP**	**EXP**	**PROD**	**EQU**	**EXP**	**PROD/EXP**	**PROD/EXP**
1. Zonal Representation of Demand/loads Projections	The size of the load and supply zones are important in 2 respects: 1) The large the zone the more heterogeneous the load zones are. 2) A zone is usually considered as a 'copper plate' without any congestions. The more zones a model has the better congestions can be represented and models.	Yes for WECC, EI, and ERCOT. WECC data include BC Hydro and Alberta from Canada. WECC data also includes Baja California from Mexico. EI data include Saskatchewan, Manitoba, Ontario, Quebec, New Brunswick, Nova Scotia from Canada	No. Load is built for specific time period of interest. Plexos is working on data base for EI that includes other parts of Canada. For other parts of Mexico, Plexos Australia office is working with clients Mexico. No details on how much it has done to build those databases.	Can provide nodal and zonal representations	Gridview has nodal WECC, EI, and ERCOT as standard database. It is not clear whether it has Canada in EI and Mexico in other databases	This is a highly temporally resolved model to explore imbalance implications from renewables and their cost implication. It is used for very detailed analyses of more spatially confined problems (smaller spatial scale than whole interconnected)	138 zonal representation. NET Imports from Canada are modeled. No Mexican regions are modeled	Usually performed for regional transmission operators (RTOs) within ISOs footprints. number of zones vary from footprint to footprint. Highly resolved model for very detailed transmission analyses	Zonal representation	Nodal representation transmission system. Real-time OPF as well as other highly operations related analysis	ONLY Zonal (22) representations of US zones. CA and MX is model by firm export of power using a supply curve	9 US regions (EPA model) representing demand regions. Supply of other fuels are divided into their respective coal, oil supply regions.	YES, PNNL has a dataset from the WECC that has full representation of US-CA and Baja MX transmission transfers represented. An version of the Eastern interconnection exist as well	50 states in GCAM-USA. CA and MX form one region each.	21 zones of the lower 48 States	Documentation does not explicitly discuss data availability. This tool stems from PSERC and is now maintained by 2 Univ. and RFF. It does not appear to have the data and the numerical capabilities to solve large problems	Nodal and zonal database including CA and US. it also includes an Expansion planning model as part of the suite

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		PROD	**PROD**	**PROD**	**PROD**	**PROD**	**EXP**	**PROD**	**PROD**	**PROD**	**EXP**	**EXP**	**PROD**	**EQU**	**EXP**	**PROD/EXP**	**PROD/EXP**
2. Baseline of gen/transmission	All of the tool have databases that are baselined or benchmarked to some other credible data set. Most models are benchmarked to EIA, but commercial products (PROMOD) may provide independent services.	Benchmarked by vendor. For WECC, committee will publish highly calibrated datasets for WECC.	Benchmarked by vendor.	Benchmarked by vendor.	Benchmarked by vendor.	EIA and other sources	EIA	Benchmarked by vendor.	EIA and other sources	NO	EIA	Yes, baseline for generation, no baseline for transmission	YES, usually based on EIA data for a particular year	EIA and other sources	EIA	?	By vendor
3. Cost for technology and fuels for future years	Capital cost trajectory is only relevant for capacity expansion. Fuels expectations are important for future years for both PROD and EXP.	Yes	No	No: not relevant for PROD as model only dispatches existing technologies	No: not relevant for PROD as model only dispatches existing technologies	No: not relevant for PROD as model only dispatches existing technologies	Yes	No, not relevant for PROD	No: not relevant for PROD as model only dispatches existing technologies	No, not relevant for PROD	YES	Yes, as adopted by EPA	No cost of technology. Only cost of future fuels for electricity production	Yes	Yes	Yes	Yes
4. Data to represent constraints on foreign systems or trade	For modeling sensitivities of increased or decreased cross-border trade US-CA or US-Mx, it is important to vary the constraints into or out of the US into neighboring countries	All paths for powerflow across the border have their limits.	All paths for powerflow across the border have their limits	Flowgates or transmission line constraints can be set by users. The line flows constraints are represented in terms of power limits NOT energy trade limits over a duration of month or year	Flowgates or transmission line constraints can be set by users. The line flows constraints are represented in terms of power limits NOT energy trade limits over a duration of month or year	Yes, constraints can be freely defined	Not aware that they currently exist, but can be easily implemented	Very highly resolved and detailed model. It allows analyst to explore constraints on transmission and generation	Yes, model can be constrained by capacity or energy. It was designed to model hydro storage and other storage technology that are energy limited	Yes, highly customizable to represent AC power constraints in a very detailed form.	YES	NO No current transmissions represented from the US into CA or MX.	Yes, model has constraints with respect to transfer capabilities as well as generation constraints Model can incorporate any kind of constraints	The 50 state version of GCAM (GCAM-USA) is embedded within the 32-region global version of GCAM. However electricity trade across countries is not currently represented.	Yes, RFF appears to be working on developing the data set	Can be implemented	Yes

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		PROD	**PROD**	**PROD**	**PROD**	**PROD**	**EXP**	**PROD**	**PROD**	**PROD**	**EXP**	**EXP**	**PROD**	**EQU**	**EXP**	**PROD/EXP**	**PROD/EXP**
5. Demand and supply curves for market representations	This is only applicable for EQU models. Some PROD models have an implicit representation of a supply curve by estimating the cost for DR	Not directly but through cost curve of each generator in the database and demand curves for individual groups.	Not directly but through cost curve of each generator in the database.	Demand response can be modelled as a resource that has a cost characteristics similar to a generator	Demand response can be modelled as a resource that has a cost characteristics similar to a generator	Demand response can be modelled as a resource that has a cost characteristics similar to a generator	This model does not determine the demand/supply equilibrium. It assumes it and then selects the optimal technology mix	Not directly. Demand and Supply curves can be generated as an outcome of many run. They as not input to the model	Demand response can be modelled as a resource that has a cost characteristics similar to a generator	Demand is represented at each transmission node. SCOPE does not use supply and demand curves	No demand is model in CA nor MX. Side cases of the AEO were explored w.r.t. to Canadian gas and crude oil imports	Supply of primary energy is represented by means of supply curves. Primary energy is converted to secondary forms (e.g. electricity). Model finds optimal supply chains to meet all demands.	Demands are given as input, demand response is currently not represented but could be as a negative generation. Supply curves do not exist	Supply of primary energy is represented by means of supply curves. Primary energy is converted to secondary forms (e.g. electricity). Electricity competes with other secondary forms of energy in three end-use sectors (transport, buildings and industry).	Supply of primary energy yis provided in a supply curve	No	
6. QUESTION 1: Quality of data: **- is it same as for US?** **- if not, how is it different**	Self explanatory	Yes , it is assumed that quality of data is uniform across countries. Data from NERC are all checked for quality regardless from which country they come. . Actual quality control can only be verified in actual experiments, which need to be done routinely as the grid evolves	Yes , it is assumed that quality of data is uniform across countries. Data from NERC are all checked for quality regardless from which country they come. . Actual quality control can only be verified in actual experiments, which need to be done routinely as the grid evolves	Yes , it is assumed that quality of data is uniform across countries. Data from NERC are all checked for quality regardless from which country they come. . Actual quality control can only be verified in actual experiments, which need to be done routinely as the grid evolves	Yes , it is assumed that quality of data is uniform across countries. Data from NERC are all checked for quality regardless from which country they come. . Actual quality control can only be verified in actual experiments, which need to be done routinely as the grid evolves	depends on which data set is being used. It uses secondary data from other vendors.	Does not currently have international data	Yes , it is assumed that quality of data is uniform across countries. Data from NERC are all checked for quality regardless from which country they come. . Actual quality control can only be verified in actual experiments, which need to be done routinely as the grid evolves	This tool is used by individual utility companies for their particular footprint. Data for CA and MX would need to be obtain from somewhere else. Quality then depends on data supplier	Model is used for real-time operational analysis. In this context it is highly calibrated for the specific footprint for which it is applied		EPA used it for US analyses. Most of the analyses were performed in an international context. It is difficult to assess quality of data if the sources are multiple	depends on which data set is being used. It uses secondary data from other vendors.	Yes	Data for CA are not available	N/A	

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		PROD	PROD	PROD	PROD	PROD	EXP	PROD	PROD	PROD	EXP	EXP	PROD	EQU	EXP	PROD/EXP	PROD/EXP
7. Nat. Lab.: having the program or access to it	Self explanatory	PNNL	NREL, PNNL	NREL access through GE subcontractor	NREL	NREL	NREL proprietary	NO	Yes, ANL developed it	NO	LBNL, NREL, PNNL	BNL has been using it for IEA, EIA, EPA for many decades	PNNL	PNNL made available on server	Not known	Free down loadable	
8. Relevant time steps	This is important from a perspective of the ability to model renewable integration problems. With subhourly time steps ramping issues within the hours would be revealed and the system response can be assessed.	Hourly	Subhourly	Hourly	Sub-hourly	Seconds to hours	Load duration curve with 9 (?) timeslides	hourly	hourly	Sub-hourly	Load duration curve with 9 (?) timeslides	Annual	subhourly	5 year.	Load duration curve with 12 time slices (3 seasons * 4 time blocks)	It solved DC OPF as well as expansion planning by years	
9. Generation represented	This looks at how the generation is represented. It provides insights into the key methodology of the model.	Optimally dispatched	Optimally dispatched	Optimally dispatched	Optimally dispatched	Optimally dispatched at hourly, and sub-minute	Supply stack optimally determined	Optimally dispatched	Optimally dispatched to maximize net revenues	optimally dispatch OPF, as well as minimal loss objectives	Supply stack optimally determined	all fuels power generation resources. It also represents oil, natural gas and nuclear markets	optimally dispatched	Logit-choice competition among fuel types	Supply stack optimally determined	Yes	
10. Transmission represented	This looks at the resolution of the transmission network.	Only if run nodally	Only if run nodally	Only if run nodally	Only if run nodally	DC transmission network	DC transfer capability across 138 zones	AC and DC properties for nodal representation	Only as flow interface between multiple zones	Nodal AC power flow		For the US, transmission is only represented on a course zonal interface basis	Only if run nodally	The transmission network is not explicitly modeled, although T&D losses are accounted for.	transfer can be limited	Yes	
11. Technology Cost determined endogenously	Important. The methodology of how to represent 'learning curves is really important in the outcome of the model. User-defined technological improvements are not as consistent with model defined learning.	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	No. all costs are provided by input in database. Heat rate usually represented as a linear or quadratic response	Yes, determined ad a function of deployed capacity	BNL worked on learning curve representation. Not clear how much this is now available within the general model	No. All of the technology characteristics are determined as input.	No	Similar approach to NEMS	NO	

Brief Descriptions of Modeling Tools

Figure 1 below shows the simulation horizon and the time step increments of a set of models and tools that are relevant for the North American coordination discussion. The capacity expansion models usually run in time increments of 1 year for several decades out into the future. The spatial domain is usually an interconnection or the entire country (US or CA). Their output is then usually used as input into an operational model that verifies the technical feasibility of the capacity additions to be integrated into the grid. This verification is performed through operations models. The industry usually performs distribution system modeling separate from bulkpower simulations. The underlying methodologies are similar. However, distribution system need highly detailed representation of the infrastructure and the individual customer load behavior. The spatial domain of a distribution system covers usually 100-500 homes, buildings, or industrial customers. Bulkpower system simulations are usually performed with some averaged or lumped system load assumptions. Their spatial domains are usually much larger and comprises many utility zones within an interconnection.

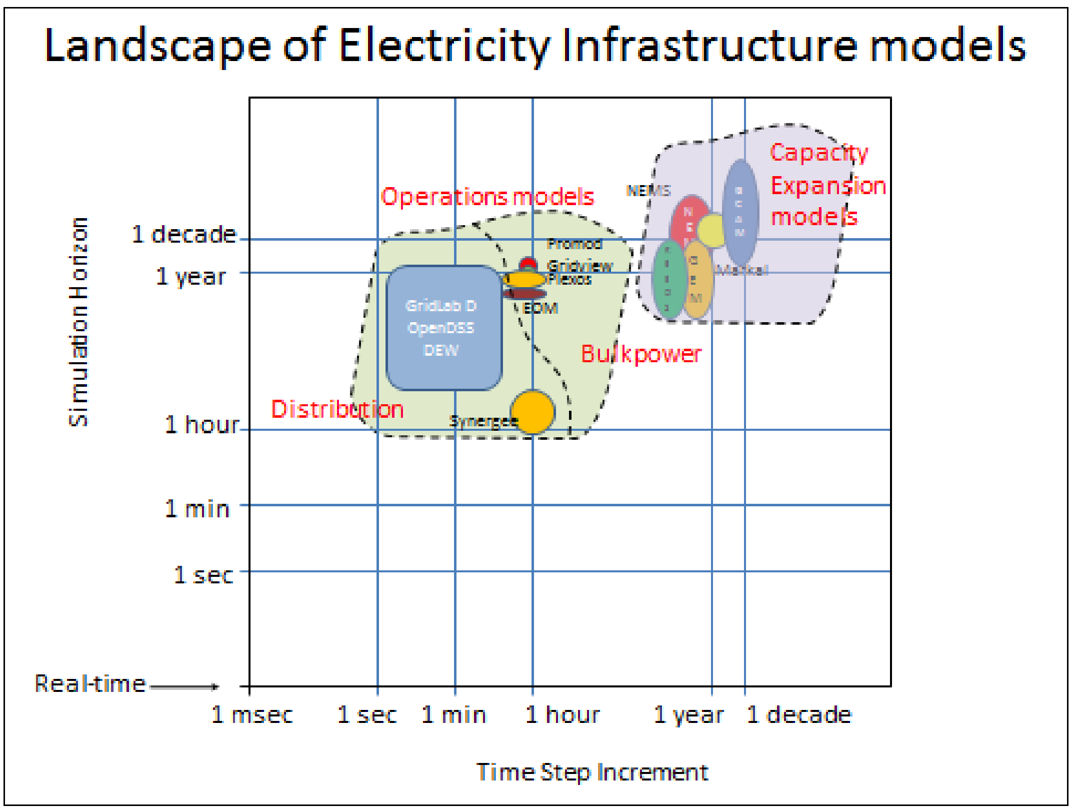

Figure 1: Landscape of Relevant Models. Note: there are: a) capacity expansion models (EXP), b) operations models for bulkpower (PROD) and distribution systems. The equilibrium model (EQU) is subsumed in the capacity expansion models envelope.

Production Cost Models:

Purpose

Production Cost models are used for scheduling generation resources in vertically integrated utilities as well as in ISO competitive whole sale markets. The models seek minimal cost dispatch of generators to meet load as well as maintain reserve requirements and other system operational requirements. Tools are used in an operational setting as well as for future planning purposes.

Scope

Operational use: Vertically integrated utility organizations use this tool for daily and hourly dispatch scheduling as well as ISO competitive markets that check if the cleared markets are operationally viable or if out-of-market dispatch must be used to resolve operational constraints.

Planning use: vertically integrated utilities apply production cost models to explore operational impacts to a policy or technology intervention of the current and future system build-out.   IOUs use production cost models for their integrated resource planning (IRP) proceedings.

Modeling

Power market simulation software package PLEXOS® is one of several tools used to model market operations. The build-in security constrained unit commitment (SCUC) algorithm consists of two major logics: Unit Commitment using Mixed Integer Programming and Network Application as depicted in Figure 2.

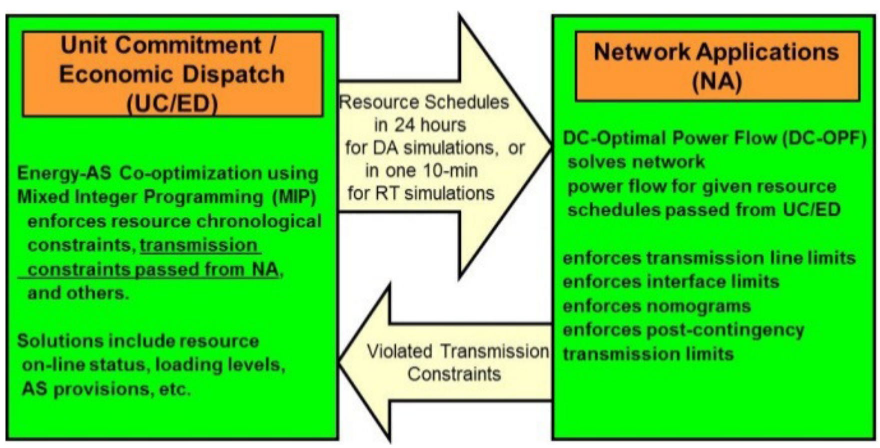

Figure 2.   PLEXOS Security-Constrained Unit Commitment and Economic Dispatch Algorithm

The unit commitment and economic dispatch (UC/ED) logic performs the energy and ancillary services co-optimization using mixed integer programming that enforces all resource and operation constraints. The UC/ED logic commits and dispatches resources to balance the system energy demand while meeting the system reserve requirements.

The resource schedules from the UC/ED are passed to the network applications logic, which solves the DC optimal power flow (OPF) in a manner that enforces the power flow limits and nomograms[1]. If contingencies are defined, the network applications logic also performs the contingency analysis. If there are any transmission limit violations, these transmission limits are passed to the UC/ED logic to re-run UC/ED. These iterations continue until all transmission limit violations are resolved. Thus, the co-optimization solution of energy-ancillary services-DC-OPF is reached.

Similar algorithms are used by many Independent System Operator (ISO) and Regional Transmission Organization (RTO) market scheduling software packages. Some ISO/RTO market scheduling software packages may rather use AC-OPF in the network applications logic.

Outcome of modeling

The output of the models is highly complex, very data-intensive, and requires much post processing and experience to slice and dice the vast amount of data. When used for a mid-term planning process, the analyst has experience to look for certain power flow conditions or unmet loads or unserved energy in certain regions during certain load conditions. There is generally not ONE output of the model. There are literally hundreds of reports that can be generated to get very detailed system behavior information from each model run.

The value of this modeling particularly when used as a planning tool is to explore any operational violations (transmission violations, unserved energy) and cost implications (either in terms of LMP or total production cost over a period of time (month, year)) in response to a technology or policy intervention. So, for instance, one may design a scenario that postulate x MW of additional wind generation capacity in a certain footprint. The goal of this scenario definition is to explore the change in dispatch and its associated change in production cost or marginal cost and emission intensity as a consequence of the wind capacity addition (of x MW).

Usually several tens of different scenarios are run to explore implications of various technology and policy interventions.

PROMOD

Suitability to Evaluating North America Harmonization Questions

This tool would be suitable to explore scenarios that attempt to quantify the value of Canadian resources to be marketed for US grid services. However, it would require that the analyst hypothesizes a future generation mix and transmission infrastructure between Canada and the US to explore operational opportunities for Canadian/US coordination. PROMOD will not select future technologies deployments. It optimizes existing generators. The datasets for the Canadian generators are available and likely to be of the same quality of those for the US.

Model Overview

PROMOD is a commercial tool for utility traders and engineering planners. PROMOD is based on an optimization approach that searches for a least-cost security constrained unit commitment (SCUC) and security constrained economic dispatch (SCED) of generators within a transmission system. The WECC in the 2000s used it as a planning tool for transmission planning in its 10-year planning activities. MISO has been using it as well. The vendor, ABB (formerly Ventyx) provides technical modeling support as well as data and data support. Databases are frequently updated, at least once per year to reflect upgrades in the transmission systems, operating requirements, some markets designs and, and, most

[1] Nomogram: is generally expressed in a chart that represents allowable operating conditions within a multi-parameter space.

importantly to capture retirements and new additions of the power plant fleet. Data represent all generators that are part of the North American Interconnection, except for Mexico. The Mexican generators included in the US databases are those in Baja that are connected to the WECC. The PROMOD model runs for one full year with hourly time increments. The model can be run in a zonal representation or in a nodal mode, which provides more detail regarding the transmission congestion. It simplifies the power flow calculation by linearized DC flow equations.

Major Studies Using This Model

- WECC had been using PROMOD in its transmission planning processes until very recently when it decided to use GridView. All of the transmission planning studies during the late 2000s and early 2010s have been performed with PROMOD.

- MISO has been using PROMOD for its planning processes as well. Several wind integration studies have been published by MISO.

- National Assessment of Energy Storage for Balancing Services and Energy Arbitrage. PNNL. http://energyenvironment.pnnl.gov/pdf/National_Assessment_Storage_PHASE_II_vol_1_final.pdf

Official Model Documentation

- http://new.abb.com/enterprise-software/energy-portfolio-management/market-analysis/promod-iv

Vendor Website

- http://new.abb.com/enterprise-software/

Plexos

Suitability to Evaluating North America Harmonization Questions

The suitability of Plexos for a market value exploration for Canadian/US coordination is similar to that for PROMOD from an underlying methodology perspective. The disadvantage would be the data for Canadian grid resources do not currently exist.

Model Overview

Plexos is a commercial tool for utility traders and engineering planners. Very similar to the ABB's PROMOD, Plexos is designed to address and explore the utility market conditions. Plexos has been introduced into the utility market in the US recently, by offering sub-hourly dispatch of all generators. Because of the sub-hourly time increment, Plexos has been used in recent renewable integration studies that focus on some of the ramping issues because of increasing contribution by solar and wind generation. The vendor provides data support for all US regions. However, Canadian resources are not available at this time. It simplifies the power flow through the transmission network as DC flow.

Major Studies Using This Model

- http://energyexemplar.com/publications/research-publications/

Official Model Documentation

- http://energyexemplar.com/software/plexos-desktop-edition/

Vendor Website

More information: http://energyexemplar.com

Maps

Suitability to Evaluating North America Harmonization Questions

Suitability of the MAPS is very similar to the PROMOD and Plexos.

Narrative Summary

MAPS is very similar to PROMOD in both its underlying methodologies as well as in the data support by the vendor (GE Energy Consulting). NREL's 2010 Western Wind and Solar Integration Study utilized MAPS. MAPS is designed to resolve time on an hourly basis. MAPS is part of GE's software suite that provides data transfer across different tools seamlessly. For instance, MAPS can provide hourly results to a higher time-resolved model that simulates the dynamic components of grid assets to explore dynamic stability of the grid.

MAPS simplifies the power flow through the transmission network as DC flow.

Major Studies Using This Model

- NREL's 2010 Western Wind and Solar Integration Study: available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.393.9325&rep=rep1&type=pdf

Official Model Documentation

- General information: http://www.geenergyconsulting.com/practice-area/software-products/maps

Vendor Website

- http://www.geenergyconsulting.com

GridView

Suitability to Evaluating North America Harmonization Questions

Suitability of the GridView is very similar to the PROMOD and Plexos. Since WECC is currently using GridView, the most recent database would be available for Western US/CA study.

Narrative Summary

GridView is similar to PROMOD, Plexos, and MAPS. The vendor of GridView, ABB, provides data support for the model as service such that updated databases of GridView reflect the evolving grid. NREL's SunShot Vision Study and the more recently Renewable Electricity Futures Study utilized GridView to validate the deliverability of capacity addition that an expansion planning model (in this particular case it was NREL's ReEDS) projected.

Furthermore, noteworthy is that the WECC uses GridView to perform economic analyses for the transmission expansion planning activities. With that comes high quality validated datasets that WECC makes available to its members. The key reason for WECC to use GridView was based on the fact the GridView integrates with a dynamic analysis tool PSSE to perform dynamic analysis.

Major Studies Using This Model

- NREL's SunShot Vision Study 2012: http://www.nrel.gov/docs/fy12osti/53310.pdf
- NREL's Renewable Energy Futures Study (2013): http://www.nrel.gov/docs/fy13osti/52409-ES.pdf
- WECC's Transmission Expansion Planning Department (2015): https://www.**wecc**.biz/Reliability/**TEPPC**-Value-Proposition.docx

Official Model Documentation

- https://library.e.abb.com/public/581366a0c212c93ac1256fda00488562/Gridview%20Brochure.pdf

Vendor Website

- http://www.abb.us/industries/us/9AAC30301274.aspx?country=US

SCOPE

Suitability to Evaluating North America Harmonization Questions

This model is very detailed and usually customized for control centers. While technically suitable for the desired North American harmonization analysis, it may not be a good candidate because of the high complexity of input data required, which may not be relevant for an analysis about future grid scenarios.

Narrative Summary

Nexant SCOPE® is a sophisticated software application for power system engineers. It is used for very utility-specific and highly detailed analysis features, including:

- Transmission planning-conducting studies of transmission equipment feasibility, siting, interconnection, and engineering design
- Decision-making under outage conditions-providing a solution that enables operators and engineers to make decisions even when the base case is significantly degraded due to outages or bad states
- Operational planning-performing rapid powerflow and contingency analysis studies with user-defined contingency lists to confirm reliability status-such as powerflow and contingency analysis and performing look-ahead simulations
- Optimal power flow (OPF)-offering an unparalleled choice of objective functions (single or combined) and constraint definitions to enable modeling and study of remedial control actions, MW transfer maximization, loss minimization, capacitor installation (sizing and placement), etc.

- Market simulations-simulating economic cost or price-based dispatch in mixed spot and bilateral markets, as well as comprehensive zonal and nodal location marginal pricing
- Reactive power prices-defining the value of reactive power and setting the price for generation bids in day-ahead or real-time markets

Nexant SCOPE is implemented in over 120 control centers world-wide as dispatcher powerflow, real-time contingency analysis and real-time OPF.

Major Studies Using This Model

- Most studies are performed directly for utility clients and, thus, are not published.

Official Model Documentation

- http://server.nexant.com/ess/product_scope.aspx

Vendor Website

- http://server.nexant.com

RIM

Suitability to Evaluating North America Harmonization Questions

While the model is technically suitable to perform a North American harmonization analysis, the specific feature sets of climate change of RIM are not likely to be utilized. As with all of the other production cost models, the biggest challenge would be to develop the data set for cross-border trades.

Narrative Summary

PNNL's Renewable Integration Model (RIM) features two functions: a) modeling the security constrained unit commitment (SCUD) and security constrained economic dispatch (SCED). Currently the SCUC is used under the acronym Electricity Operating Model (EOM). It has been used for research purposes to explore electric grid stress case scenarios under extreme weather conditions such as drought and concurrent heat wave conditions. The model is calibrated to the PROMOD results for both the WECC and the Eastern Interconnection. The model uses the full WECC data set that includes all of the Canadian and Mexican that are part of the WECC. For the eastern interconnection, the data set includes all US generators and a reduced set of Canadian generators. Mexican generators east of the Mississippi are not represented.

The model simulates the unit commitment problem in hourly time steps. It uses a linearized DC power flow representation.

Major Studies Using This Model

Studies perform on production cost modelling efficiency:

http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=7286561&url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel7%2F7271236%2F7285590%2F07286561.pdf%3Farnumber%3D7286561

Official Model Documentation

- No currently posted on the publish website

UPLAN Network Power Model

Production Cost model

Suitability to Evaluating North America Harmonization Questions

This model could be suited for reliability and economic impacts of a cross-border harmonization. It would require a particular scenario definition of a project to be analyzed. Because of its high definition in representing existing market designs of US ISOs, UPLAN would be most suitable if there is a scenario that involves NYISO or ISO-NE.

Narrative Summary

UPLAN performs SCUD and SCED computations both in a zonal and nodal transmission representation. It provides the option of solving for DC as well as AC power flows. AC power flow is more time-consuming as additional voltage variables are to be computed. UPLAN has been applied for WECC sized problems. It has been implemented at the ISO-NE. It represents specific market designs such co-optimization of Day-ahead markets and ancillary markets.

Major Studies Using This Model

- Study results are generally not published. Most studies are perform for utility and ISO/RTO clients

Official Model Documentation

- General information: http://www.energyonline.com/products/uplane.aspx

Vendor Website

- http://www.energyonline.com

Capacity Expansion Models:

Purpose

The purpose of the capacity expansion plan is to develop an investment strategy that will explore trade-offs across a portfolio of available generation technologies to meet a set of cost objectives, usually cost minimization, and a set of emission or other environmental targets or constraints. The investment strategy is expressed in a series of capacity additions (new plants) for generation and sometimes for transmission and retirements or upgrades of existing plants. The results are generally represented by years, by technology, by zones or regions over the entire projection horizon.

Scope

In most cases, the investment plan is developed for a large electric footprint, which could be for an entire interconnection or for an RTO area. Capacity plans are generally developed by utility organization for rate case proceeding or for submission of an Integrated Resource Plan (IRP). The projection horizon is generally 20 to 30 years.

Modeling

The models used for capacity expansion planning are mostly based on cost minimization strategies that will minimize the net present cost over a study period (say 20 to 30 years) to meet load growth and regulatory constraints, such as planning reserve margins and emission targets. The model is seeking feasible solutions that trade-off cost and performance characteristics of a portfolio of conventional and new generation technologies to meet load. The optimization is usually formulated as a zonal problem, whereby the model can decide to build a plant in a particular zone. Zones are generally connected with adjacent zones for transferring electric energy.

The load is - in most models - represented by a load duration curve, in most cases by a simplified load duration curve that consists of load blocks that are sorted in descending order from highest load on the left to the lowest load block on the right. A typical simplified load duration curve consists of 7 load blocks or load slices. A chronological hourly load profile for one year (8760 hours) can be transferred into a 7 load-slice-duration curve by grouping the hours and seasons into the following load slices:

- Summer or winter peak hour (highest hourly load)
- Summer day time (6:00 to 18:00)
- Summer night time (19:00 to 5:00)
- Fall and spring day time (6:00 to 18:00)
- Fall and spring night time (19:00 to 5:00)
- Winter day time (6:00 to 18:00)
- Winter night time (19:00 to 5:00)

The use of load slides rather than 8760 individual hours reduced the optimization problem significantly. Rather than seeking the optimal solution for 8760 individual states in the time domain, only 7 states must be determined. This is a significant reduction in the complexity of the optimization problem. However, this simplification comes at the expense of losing the notion of chronological time. The chronology of time is important for determining ramp rates and dispatching short term demand response or performing daily load-shifting with energy storage technologies. To represent dispatch strategies such as DR or energy storage would require a chronological representation of the problem.

Outcome of modeling

The outcome of the model is a capacity expansion plan, sometimes also referred to as capacity additions specified by region and years in MW (capacity) of a new plant to be built. In addition, it provides capacity additions by years for transfer increments between two adjacent zones. Furthermore, most models can determine economic retirement of plants, which is usually determined by comparing the revenue expectations for a particular plant with its cost for operations and the cost recovery, if not fully depreciated.

ReEDS

Suitability to Evaluating North America Harmonization Questions

ReEDS is well suited for a North American Harmonization study, if the goal is to seek a grid future scenario for a time in the future, say 10 or 20 years out. In this case, ReEDS would project out new generation capacity given policy directives or options for Canada and the US. ReEDS has primarily been used for the US footprint. However, ReEDS datasets exist for Canada as well. NREL has performed some US/CA analyses. Furthermore, ReEDS would not be the appropriate tool if one wants to examine the reliability related questions. As a capacity expansion planning model, it assumes that reliability is always maintained.

Narrative Summary

NREL's Regional Energy Deployment System (ReEDS) is one of the most comprehensive electric capacity expansion models with respect to the spatial resolution and the resource representation. ReEDS represents 138 balancing area and a total of 356 supply region that represents biomass, solar, wind resources as well as fossil fuel supply (i.e., oil, natural gas, and coal).

As an expansion planning model, ReEDS seeks cost-optimal technology choices to meet future electricity demands within the 138 balancing areas. Given cost and performance characterization of the generation technology as well as transmission, ReEDS develops for a year the optimal build-decisions of generation and transmission capacity that minimizes net present cost for operating the entire US grid and the expenditures for capacity additions. ReEDS has been used in the Renewable Electricity Futures Study (2013).

Major Studies Using This Model

- NREL's Renewable Energy Futures Study (2013): http://www.nrel.gov/docs/fy13osti/52409-ES.pdf
- US/Canada study: http://www.nrel.gov/docs/fy13osti/56724.pdf

Official Model Documentation

- http://www.nrel.gov/analysis/reeds/description.html

Developer Website

- http://www.nrel.gov

NEMS

Suitability to Evaluating North America Harmonization Questions

While NEMS's ECP model would be suitable for an exploration of North American harmonization of the electricity markets, the challenge would be to expand the regional representation into Canada.

Narrative Summary

The Energy Information Administration's (EIA's) National Energy Modeling System (NEMS) is one of the most comprehensive energy system modeling used for exploring complex integrated energy analyses across all energy sectors for the US. Within the individual modeling system that features individual demand models for transportation, industrial, residential and commercial sectors and individual supply models for oil and gas, and electricity. Within the electricity market model (EMM), NEMS has an Expansion Planning Model (ECP) that makes generation and transmission planning decision based on cost-minimization principles to meet future electricity demands. The ECP has 22 US regions. Canadian regions are not represented. It provides a very sophisticated technology cost and performance representation that models cost decline of future technologies, known as 'learning curves'.

Major Studies Using This Model

- All Annual Energy Outlooks (AEOs) since the late 1980s are performed using NEMS

Official Model Documentation

- Model documentations: https://www.eia.gov/forecasts/aeo/nems/documentation/electricity/pdf/m068%282014%29.pdf

Developer Website

- https://www.eia.gov

Markal/Times Models

Suitability to Evaluating North America Harmonization Questions

As stated for the NEMS model, Markal/Times could be suitable for an exploration of an North American electricity market as an expansion planning model. EPA's US model would then need to be combined with the Canadian model and to explore cross-border trades. Canadian models exist. However, they may be dated.

Narrative Summary

MARKAL and then the successor TIMES are categorized as an EXPANSION PLANNING model. The model chooses an optimal energy flow path starting from primary energy to meet future energy demands. It is based on linear optimization techniques that search for least cost pathways among all of the energy conversion processes to meet future demands.

The model represents generally all energy supply and demand sectors, not only electricity. For the US representation EPA developed a MARKAL model with 9 regions (see figure below). It only contains US regions. The model optimally (cost-minimal approach) selects technologies to meet demand on a yearly basis. As such, it does not represent delivery and other operational complexity that would provide insights into reliability or resiliency issues. It is designed to answer questions about likely policy implications with respect to technology choices.

MARKAL was developed in a cooperative multinational project over a period of almost two decades by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. The ETSAP executive committee has decided to promote TIMES for new users starting winter 2008. However, MARKAL code will continue to be supported in its current form and it is still an option for new users who may have their own reasons to choose it over TIMES.

MARKAL is a generic model tailored by the input data to represent the evolution over a period of usually 40 to 50 years of a specific energy system at the national, regional, state or province, or community level. The number of users of the MARKAL family of models has multiplied to 77 institutions in 37 countries, many with developing economies, promising to continue and broaden these accomplishments.

Some uses of MARKAL:

- to identify least-cost energy systems
- to identify cost-effective responses to restrictions on emissions
- to perform prospective analysis of long-term energy balances under different scenarios
- to evaluate new technologies and priorities for R&D
- to evaluate the effects of regulations, taxes, and subsidies
- to project inventories of greenhouse gas emissions
- to estimate the value of regional cooperation

The main output TIMES are energy system configurations, which meet the end-use energy service demands at least cost while also adhering to the various constraints (e.g 80% emissions reduction, 40% renewable electricity penetration). In the first instance, TIMES model addresses the question: is the target feasible? If an energy system is possible, it can then be examined, at what cost? The model outputs are energy flows, energy commodity prices, GHG emissions, capacities of technologies, energy costs and marginal emissions abatement costs.

Major Studies Using This Model

- EPA database for US: http://nepis.epa.gov/Exe/ZyPDF.cgi/P100I4RX.PDF?Dockey=P100I4RX.PDF

Official Model Documentation

https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=278925&simpleSearch=1&searchAll=EPA+U.S.+Nine-Region+MARKAL+Database+-+Database+Documentation

Overview of TIMES Modelling Tool**: http://www.iea-etsap.org/web/Times.asp**)

additional information available:

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models. ETSAP.
Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES Model - PART I 1–78

Canadian studies performed using MARKAL

(Berger, C., Dubois, R., Haurie, A., Lessard, E., and Waaub, J.P.) "Canadian MARKAL: An advanced linear programming system for energy and environmental modelling", INFOR, v. 20 (August 1992), pp. 114-125.

(and Waaub, J.P.), "CO2 Emission Reductions With Cooperation in Quebec and Ontario: A MARKAL perspective", Energy Studies Review, v. 4, no. 3 (1992), pp. 278-296.

Developer Website

http://www.iea-etsap.org/

Haiku

Suitability to Evaluating North America Harmonization Questions

Very suitable for cross-border analysis across the North American Continent. It has been used for such a study.

Narrative Summary

Resources for the Future's (RFF's) HAIKU model simulates regional electricity markets and interregional electricity trades in the continental US. The model accounts for capacity expansion planning, investment and retirement over a multi-year horizon and for system operations over seasons of the year and times of day. Electricity demand is represented by price-sensitive demand schedules by customer class, and changes in the demand can be implemented through investments in energy efficiency, time of day pricing and other regulatory changes.

The model identifies least-cost compliance strategies for compliance with various types of regulations of sulfur dioxide, nitrogen oxides, carbon dioxide, and mercury emissions. Market structure is represented by cost-of-service (average cost) pricing and market-based (marginal cost) pricing in various regions.

The Haiku model has a spatial resolution of 21 regions of the lower 48 states. The regions are similar, not congruent, with NEMS region definition. As other expansion planning models, loads as driving force is represented by a simplified load duration curve that consists of time slices, which represent the energy requirements in certain time blocks of a day in a particular season. The technology representation is similar to the learning curve methodology applied in EIA's NEMS model [Paul et al., 2009].

RFF proposed to explore opportunities for transboundary regulatory and planning harmonization (see: http://www.rff.org/events/event/2015-10/electric-power-united-states-canada-and-mexico-opportunities-transboundary) using the Haiku model. The model will address the benefits in terms of cost savings and emissions reduction of a co-optimized Canadian/US and US/Mexican expansion planning process. The main focus is on resources sharing across the borders primarily from an energy services perspective. The sub-hourly synergies that a cross-border co-optimization may yield are unlikely to be addressed using the Haiku model.

Major Studies Using This Model

- US/CA/MX transboundary opportunities: http://www.rff.org/events/event/2015-10/electric-power-united-states-canada-and-mexico-opportunities-transboundary

Official Model Documentation

- Paul, A., Burtraw, D., Palmer, K. Haiku Documentation: RFF's Electricity Market Model. Version 2.0. January 2009. Resources for the Future. Available: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-Rpt-Haiku.v2.0.pdf

Developer Website

http://www.rff.org

E4ST

Expansion Planning and production cost model

Suitability to Evaluating North America Harmonization Questions

It remains unclear if this model is suitable for a North American study. Several case studies are provided by the developer; among them are data sets for Canada and Mexico. It is unclear as to whether these data sets are sufficient for an in-depth study.

Narrative Summary

The Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST) was developed by faculty and research staff at Cornell and Arizona State Universities and at Resources for the Future, with support from the U. S. Department of Energy's CERTS program as well as the Power Systems Energy Research Center.

E4ST consists of a set of software toolboxes that can be used to estimate present and future operating and investment states of an electric power system, including generator dispatches, generator entry and retirement, locational prices, fixed and fuel costs, air emissions, and environmental damages. The E4ST software toolboxes can be used with suitable data from any part of the world.

E4ST can be applied to detailed system models. Algorithms are included that simulate the economic operation of the power grid, in response to the model-user's projections of economic factors (e.g. fuel prices), government incentives or environmental regulations. Simultaneously, the algorithms project and implement the economical investment and retirement of generation over time, by location. The algorithms are designed to maintain the redundancy necessary for service reliability.

E4ST is useful for both energy- and environmental-policy planning purposes. It accounts for short and long-term feedbacks between energy and environmental policies. It can be used to project the operation and evolution of the power system under any combination of prices, demand patterns, and policies specified by the user. It can calculate the net benefits of any policy simulated, and disaggregate them into the benefits or costs for customers, generation owners, the system operator, the government, public health, and the environment.

In addition, E4ST can be used as a transmission planning tool to explore the consequences of network changes. The existing electric transmission system is fixed throughout these simulations, and only the generator dispatches and customer loads respond endogenously, but the user can change the transmission network and re-run the simulation to calculate the effects of the change, potentially repeating this thousands of times to test many different transmission system investment scenarios.

The model is based on a Matlab runtime system, which allows the user to use a rich library of algorithms. However, the universality of the libraries tends to be less computationally efficient, which limits the model size to smaller models (i.e., smaller numbers of decision variables). Several case studies are provided by the developer; among them are data sets for Canada and Mexico. It remains unclear as to whether these data sets are sufficient for an in-depth study.

Major Studies Using This Model

- None known

Official Model Documentation

- Daniel L. Shawhan, John T. Taber, Di Shi, Ray D. Zimmerman, Jubo Yan, Charles M. Marquet, Yingying Qi, Biao Mao, Richard E. Schuler, William D. Schulze, and Daniel J. Tylavsky, "Does a Detailed Model of the Electricity Grid Matter? Estimating the Impacts of the Regional Greenhouse Gas Initiative," *Resource and Energy Economics*, Volume 36 Issue 1, January 2014, pp. 191–207. http://dx.doi.org/10.1016/j.reseneeco.2013.11.015.

Developer Website

- http://e4st.com/

AURORAxmp

Expansion Planning & Production Cost model

Suitability to Evaluating North America Harmonization Questions

This model is suitable for a harmonization analysis. The integrated feature of expansion planning and hourly production cost modeling will allow the analyst to explore optimal investment paths and optimal operational strategies to minimize cost.

Narrative Summary

Developed by EPIS, AURORAxmp is an integrated tool to perform expansion planning analyses and product cost modeling capabilities. AURORAxmp's logic uses market economics to determine the long-term resource mix under varying future conditions including fuel prices, available generation technologies, environmental constraints, and future demand forecasts. AURORAxmp's recursive optimization process identifies the set of resources among existing and potential future resources with the highest and lowest market values to produce economically consistent capacity expansion and retirement schedules. Renewable Resource Standards (RPS) can be tested under the future conditions simulated.

AURORAxmp chooses from new resource alternatives based on the NPV of hourly market values. AURORAxmp compares those values to existing resources in an iterative process to optimize the set of new units.

This model is suitable for a harmonization analysis. The integrated feature of expansion planning and hourly production cost modeling will allow the analyst to explore optimal investment paths and optimal operational strategies to minimize cost. This tool and the appropriate scenario analysis would provide deep insight into benefits and cost savings from both energy services as well as balancing services of a cross-border electricity coordination.

Major Studies Using This Model

- The study group for developing the biannual Northwest Power Plan uses the Aurora model: https://www.nwcouncil.org/media/3375/BiennialElectric.pdf
- https://www.nwcouncil.org/energy/powerplan/7/plan

Official Model Documentation

- http://epis.com/aurora_xmp/

Vendor Website

- http://epis.com

Other Model Types:

FESTIV

Production Cost model with Automatic Govern Control

Suitability to Evaluating North America Harmonization Questions

Narrative Summary

FESTIV is a model developed by NREL to combined commonly implemented security constrained unit commitment (SCUD) and security constrained economic dispatch (SCED) with Automatic Governor Control (AGC) which is a control strategy that dispatches generators every 4- 6 seconds in order to maintain grid frequency. AGC control is necessary to balance out the scheduled generation dispatch for the next hour based on a load forecast with the actual load at time of delivery. This balancing strategy will maintain the 60 Hertz grid frequency. FESTIV is designed the study the very fine control actions that will become necessary in a power system with high penetration of variable production renewable resources such as wind and solar technologies. The draw-back for studying grid dispatch on a 4 second bases is long computational run time.

This model is well suited for specialized studies that focus on the finely balanced performance of demand and supply to maintain the grid frequency. It has not been used in many of NREL's large renewables integration studies. For general production cost modeling activities that include SCUD and SCED without AGC strategies, most researchers and analysts use commercially available production cost modeling tools.

Major Studies Using This Model

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Official Model Documentation

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Vendor Website

Additional information: http://www.nrel.gov/docs/fy11osti/50641.pdf

GTMax

Production cost model

Suitability to Evaluating North America Harmonization Questions

This model could be suited for reliability and economic impacts of a cross-border harmonization. The challenge would be to populate the database with all of the pertinent generator and transmission data necessary to run the model.

Narrative Summary

GTMax (Generation and Transmission Maximisation Model) simulates the dispatch of electric generating units and the economic trade of energy among utility companies using a network representation of the power grid [GTMax, 2009]. It was created by Argonne National Laboratory in 1995. The model is used by universities, consultants, and power companies in about 25 countries [ANL, 2009].

In GTMax, the generation and energy transactions serve electricity loads that are located at various locations throughout the simulated region, which is typically a national energy-system. The model can simulate both the electricity sector and district heating networks. The objective of GTMax is to maximize the net revenues of power systems by finding a solution that increases income while keeping expenses at a minimum. The model computes and tracks hourly energy transactions, market prices, and production costs. Using a mixed integer Linear Programming (LP) approach GTMax simultaneously solves the maximization objective for all hourly time steps in a weekly simulation period. Power flows in the model are computed using either a DC Optimal Power Flow (DCOPF) formulation or contractual power flow methodology. For several customers, the model is implemented in real-time operations with connections to SCADA systems.

GTMax has been used for a number of studies which are listed in [ANL, 2009]. Examples are: a) regional electricity-market in South-eastern Europe, b) transmission interconnection between Ethiopia and Kenya, and c) evaluation of high flows from Glen Canyon Dam in Grand Canyon National Park.

Major Studies Using This Model

- Southeast European study.

Official Model Documentation

- GTMax, 2009. Generation and Transmission Maximization (GTMax) Model, Argonne National Laboratory, 23rd April 2009,http://www.dis.anl.gov/projects/Gtmax.html
- ANL, 2009. Power Systems Analysis Program, Argonne National Laboratory, 23rd April 2009,http://www.dis.anl.gov/projects/PowerSystems.html

Vendor Website

GCAM

(Partial) Equilibrium Model

Suitability to Evaluating North America Harmonization Questions

While technically suitable to explore a North American harmonization of the electricity markets, the model would provide all interactions with other sectors as well. The challenge of that higher complexity of national and international energy market trading is that individual phenomena of interest only in the electricity sector are sometimes overwhelmed by market drivers in other sectors.

Narrative Summary

PNNL's Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. Regional population and labor productivity growth assumptions drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. Using a run period extending from 1990 – 2100 at 5 year intervals, GCAM has been used to explore the potential role of emerging energy supply technologies and the greenhouse gas consequences of specific policy measures or energy technology adoption including; CO_2 capture and storage, bioenergy, hydrogen systems, nuclear energy, renewable energy technology, and energy use technology in buildings, industry and the transportation sectors. GCAM is a Representative Concentration Pathway (RCP)-class model. This means it can be used to simulate scenarios, policies, and emission targets from various sources including the Intergovernmental Panel on Climate Change (IPCC). Output includes projections of future energy supply and demand and the resulting greenhouse gas emissions, radiative forcing and climate effects of 16 greenhouse gases, aerosols and short-lived species at 0.5×0.5 degree resolution, contingent on assumptions about future population, economy, technology, and climate mitigation policy.

Recently GCAM has been augmented to represent the US by its 50 states. This higher resolution resolves the US at a finer resolution while maintaining the spatial resolution of the other global (32) regions. Thus, Canada and Mexico are represented as individual regions. Currently there are no electricity trades represented across US borders. GCAM technology choice modeling is not based on optimization schemes, but rather on market sharing algorithm based on logit functions that rank competitiveness of technologies by levelized cost of electricity.

Major Studies Using This Model

- Many global studies performed using GCAM: http://www.globalchange.umd.edu/models/gcam/

Official Model Documentation

Vendor Website

http://wiki.umd.edu/gcam/index.php/References

Glossary

Term	Description
Balancing Area	A control area, in which a grid operator is required by NERC to maintain grid reliability. Balancing areas in regions with competitive wholesale markets are called Independent System Operators (ISOs). Balancing areas in vertically integrated markets are usually utility companies' service territory.
Equilibrium or partial equilibrium model	A model that represents supply and demands of tradable commodities to find the intersection where market equilibrate. Partial equilibrium models do not represent all of the interdependencies of a complex national and international market place – only the major interdependencies.
Expansion planning model	Simulates how the grid (generation and transmission) evolves over time. Usually based on optimization techniques that minimizes the net present value of operating and investing in new or retrofit capacity, or maximizing profits to meet load
Interconnection	Aggregation of utility zones or balancing areas which are physically interconnected via AC transmission lines. Thus, physically the interconnect functions as one "big synchronous machine" where frequency is approximately the same within the interconnection. Disturbances (trips of power plants or transmission lines) propagate throughout the entire interconnection. The US has 3 interconnections: WECC, ERCOT, and Eastern Interconnection.
Production cost model	Specific model used in the power industry to simulate generator dispatch and power flow through the transmission network to estimate cost of producing and delivering electricity. Models are generally differentiated by: AC (alternate current) models versus DC (direct current) models Zonal load/generator representation versus nodal load/generator bus representation Hourly models versus sub-hourly
Unit commitment problem (UC)	The unit commitment problem seeks an optimum solution that minimizes the cost of operating generators over a period of one day or one week. The mathematical formulation of the optimization problem includes start-up time of generators, minimal run time once a generator is broad online, as well as fuel cost and efficiencies (inverse of heat rates). This problem is mathematically more complex as it includes a mix of integer (binary) and rational variables. The optimization problem is usually referred to as MILP (mix integer linear program). The binary variables determine if an generator is on or off. The rational variables determine the setpoint of the generator (e.g., 50MW of an 100MW rated generator)
Security-constrained problem (SC)	The security constrained problem seeks viable generator and transmission conditions that allow reliable operations of a transmission network even in case of a single contingency. A contingency could be an unplanned outage of a generator or transmission line. In other words, the mathematical solution explores grid states that can operated even in the face of unexpected outages.
Security-constrained unit commitment	